Surface Network Ontology Design Patterns for Linked Topographic Data

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Abstract. The vision of Linked Topographic Data (LTD) is critical for the Semantic Web, since topographic data are fundamental to a wide range of geoscientific analyses and mapping of geographic phenomena. LTD involves a synergy between a wide variety of topographic information and services, but at its core is the theme of terrain, i.e., the shape of the earth's surface. Terrain is generally computationally represented using a continuous field data model (2-D surfaces), which contain no explicit reference to identifiable entities. This makes it difficult to share surface datasets on the Semantic Web, which requires stable and meaningful *objects* that can be assigned independent identities through URIs. Moreover, terrain is understood by people not just as a surface, but more commonly as a wide variety of discrete landforms and landscape features. The semantics of such terrain objects can be made explicit only if discrete object based spatial representations and ontologies explaining the semantics of such objects are made available. Both problems can be addressed by extracting surface networks as discrete object representations of surfaces. A surface network is a collection of shape elements (critical points, lines, and areas) that are topologically connected and collectively describe the global shape of the surface. This paper presents the first ever effort to formalize surface networks as ontology patterns, which are small ontologies intended to capture domain semantics and are easily reusable in different application contexts. The primary pattern called the Surface Network ontology design pattern (SNODP) is intended for *any* type of surface network, not just terrain surfaces, and is designed to specify only topological relationships between surface network elements. For flexibility, it leaves specification of metric properties of surface network elements to domain-specific spatial ontologies. The second pattern, Geospatial SNODP, extends SNODP for metric geographic space through alignment with the W3C recommended GeoSPARQL spatial ontology. The patterns are designed as OWL ontologies, but all axioms are presented in this paper using the compact DL notation. In addition to a strong justification of the value of these patterns, an LTD motivated case study is also presented to demonstrate how terrain surface networks can be semantically annotated and queried on the Semantic Web with the help of these ontology patterns. The scope of the patterns and their limitations, as determined by the original theory and design choices, are also clearly described through multiple discussions distributed throughout the paper.

Keywords: Linked Topographic Data, Surface Network, Topography, Ontology Design Pattern, GeoSPARQL

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1. Introduction & motivation

1.1 Ontology Design Patterns

Ontologies are essential pillars for the success of Linked Data since they define the semantics of data and clarify valid contexts of reuse. For the heterogeneous Semantic Web, ontologies need to be contextual and/or domain-oriented [17, 27]). This is especially true of the varied contexts in which geospatial data originate and get used [3]. The specialties of geospatial data led to the idea of a Geospatial Semantic Web [2, 5, 22], which is a special interpretation of the Semantic Web centered on the spatiotemporal aspects of Linked Data and other Semantic Web resources [10, 19, 54]. Due to their inherent diversity, Geospatial Semantic Web ontologies will be most useful if they are minimalist in scope, and serve only to *constrain*, not completely specify, interpretations [20-21]. Large, comprehensive ontologies, especially for a domain as varied and complex as the geospatial domain, are almost guaranteed to be useless, if not also difficult to design and reuse.

Ontology Design Patterns (ODPs) are a recent design paradigm to design small and easily reusable ontologies. ODPs are pragmatic alternatives to foundational ontologies, such as DOLCE [28], BFO [11, 47] or SUMO [31], which are too abstract to be understood by non-logicians. ODPs have become quite popular currently as a modeling solution for the heterogeneous Semantic Web [6, 48] because they are easy to understand and act as ready-to-use building blocks in larger scale ontology engineering efforts [7]. ODPs have the potential to greatly reduce duplicated work, while also facilitating data integration since they are designed to be applicable to several types of datasets [7].

A key requirement for successful ODP design is the simultaneous participation and high-level interaction between both domain and ontology engineering knowledge experts, instead of the traditional methods that limited domain experts to merely provide feedback to the ontology engineers [17]. An increasing number of geospatial patterns are being designed at Geo-Vocabulary Camps (GeoVoCamps), which are bottom-up, participatory workshops with the explicit objective of designing lightweight ontologies or ontology patterns. GeoVoCamps bring together domain experts and ontology engineers to work on a topic of common interest. The hallmarks of these workshops are the semi-formal debates and discussions, often starting at a more abstract and philosophical level, but slowly evolving into extensive grounded discussions about ontology pattern design. Semantic engineering principles and implementation method determine the final form of the pattern, which is generally available online and sometimes also documented in research publications [16, 46].

1.2 Surface Network Ontology Patterns and Linked Topographic Data

This paper reports on two closely related ontology design patterns that originated at a GeoVoCamp workshop: Surface Network ODP (SNODP) and Geospatial Surface Network ODP (GeoSNODP), which are formalizations of the core concepts of the theory of surface networks. The two surface network patterns are examples of content design patterns [35], since they formalize basic concepts of a knowledge domain—surface network theory. Work on the two patterns was initiated at the *GeoVocampSOCop2012* workshop[1], and continued for several months post the workshop through various modes of consultations between the authors. A review of surface network theory is provided in Section 2, but, in a nutshell, surface network is a mathematically elegant model for abstracting the global spatial shape of *any* surface in terms of a topological network of shape-critical points (peaks, passes, and pits), lines (ridges, course, slope, and contour lines), and areas (hills, dales and territories) [4, 29].

Two inter-related goals inspired the creation of surface network ontology design patterns. The first incentive was to understand the logical relations between various surface network features and the implications for algorithms designed to extract surface networks from digital surfaces. The most popular use case of surface networks has been terrain surfaces, which also served as the original inspiration for surface network theory. Surface networks have great relevance as intermediary structural elements for extracting complex landforms from continuous elevation surfaces [24, 44]. Thus, the ontology patterns will serve as the basis for other patterns needed to guide the extraction and annotation of more complex terrain objects.

The ability to summarize the shape of a continuous surface through discrete low-level structural features is critical to the *Linked Topographic Data* (LTD) initiative. While efforts related to LTD have been around for some time, LTD has only recently been

[1] http://www.vocamp.org/wiki/GeoVoCampSOCoP2012

formally recognized as the vision of making topographic datasets modeled as objects, networks, and fields interoperable with each other and with other datasets through Semantic Web technologies [43]. LTD is of strategic importance to national mapping organizations, such as the United States Geological Survey (USGS), the UK Ordnance Survey which are already making topographic data services aligned with the Semantic Web [9-10, 49-51]. LTD involves a synergy between a wide variety of topographic information and services, but at its core is the theme of terrain, i.e., the shape of the earth's surface, which serves as the physical backdrop for all human activities and most geophysical processes. Unfortunately, because a surface is a single-valued mathematical function [$z = f(x, y)$] of position in 2-D and contains no explicit reference to identifiable entities, it is difficult to share surface datasets on the Semantic Web, which requires stable and meaningful *objects* that can be assigned independent identities through URIs [18].

While micro-surfaces covering areas for one or group of landforms can still serve as the objects that can be assigned URIs, finding the extents of those micro-surfaces to ensure they cover the landform will always be a challenge. Spatial and other relationships between terrain objects need to be made explicit for information retrieval to realize the true potential of LTD. This cannot be solved without *object*-based representations of terrain. Supporting LTD services will need to be flexible enough to yield not just one, but several alternative assemblages of terrain objects to support different ontological commitments [25-26].

For terrain surfaces, surface networks both summarize local and global surface shape, and also serve as intermediate shape-critical elements for more complex landform extraction [24, 45]. These shape elements can also be used in automated labeling on topographic maps and other terrain visualizations, and as control points in geospatial registration and alignment of topographic datasets. Most importantly, surface networks advance the LTD agenda substantially by making terrain surface datasets available for querying and integration with other components of the Semantic Web. The discrete surface network elements can be assigned URIs and act as gateways to their source surface. The two patterns (SNODP and GeoSNODP) are essential for sharing semantically annotated surface network data on the Semantic Web. However, a surface network can capture only those types of shape elements that are defined explicitly in surface network theory; there are other possible surface parts that will remain unrepresented in surface networks. In Section 6, a case study involving a terrain dataset illustrates the benefit and limitations of the patterns in terrain mapping and information retrieval.

The theory of surface networks is generalizable to *all* surfaces, and the patterns also have been designed in the same spirit. The patterns were inspired by the topographic domain, but SNODP can be used for surfaces from all domains (e.g., medical images, chemical surfaces, surfaces of mechanical parts, anatomical) as well. Similarly, GeoSNODP is only ostensibly a specialization for the geospatial domain—it can also be used for any metric surface network as long as the simplistic Euclidean geometry primitives suffice for describing necessary shape features of the surface.

2. Review of surface network theory and its applications

2.1 Surface network theory

The basic concepts of surface network theory were proposed more than 150 years ago by mathematicians and physicists [4, 29, 39].[2] A short review covering concepts relevant for understanding the ontology patterns is provided in this section. For a comprehensive review of surface network theory, applications, and challenges, see [36-37].

Considering a two-dimensional continuous smooth closed surface floating in space with surface values relative to an internal reference point, [39] was the first to describe ideas surrounding three types of local extrema, or critical (singular) points, existing on the surface: maxima (i.e. *peaks*), minima (i.e. *pits*), and mixed extrema (*saddle points*) which are maxima across one axis and minima across another (see Fig. 1). Saddle points were later recognized to be of two types. Following the terminology of [52], a saddle point can be either a *pass* (lowest point on a ridge line connecting two peaks), or a *pale* (highest point on a course line connecting two pits). Cayley [4] independently also presented a similar but more expansive theory of surfaces, focusing on *contour lines* and *slope lines*, where contour lines run horizontally and slope lines are orthogonal to contour lines running directly up and down slopes. In addition to the necessary critical points, Cayley also identified special slope lines, *ridge lines* and *course lines*, which con-

[2] Morse theory is a more generalized mathematical theory of critical points for multiple dimensions in Euclidean space [30].

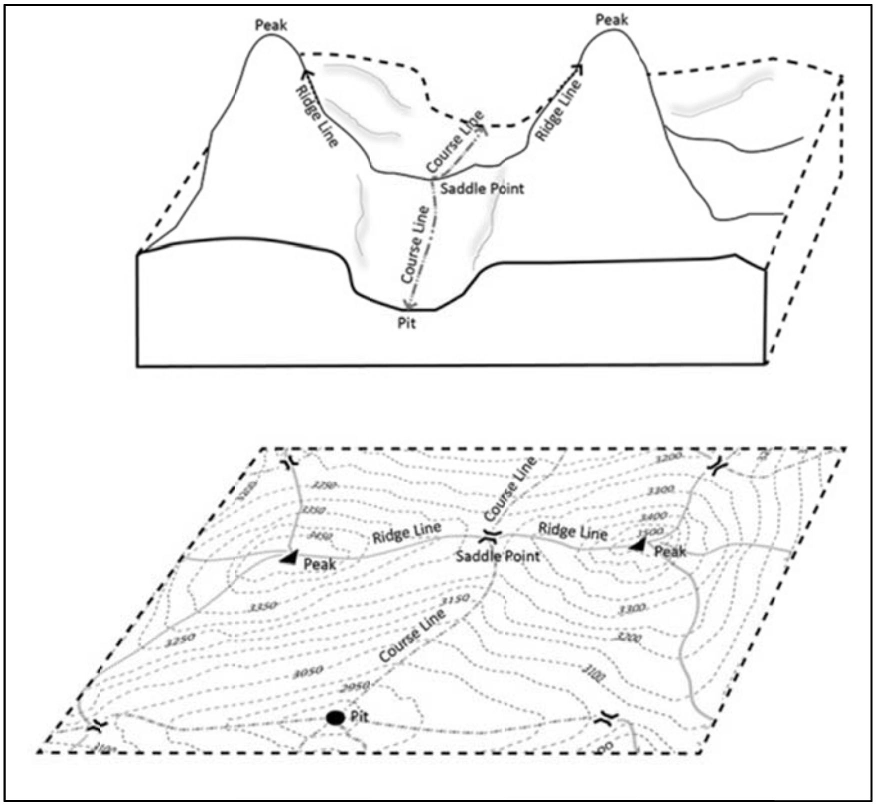

Fig. 1. Two schematic representations showing the relationships of surface network shape elements to each other and to the source surface.

nect critical points. From each normal saddle point, the slope lines of steepest ascent are called ridge lines, and ascend to peaks; the two slope lines of steepest descent from a saddle point are called course lines and descend to pits. The definitions and relations among these critical points and lines form the foundation of surface networks. Maxwell [29] again reinvented the same theory, but he added two types of regions (informally *district*s) on a surface bound by ridge-lines or course-lines. A district around a peak and bound by course-lines is a *hill,* and similarly a region around a pit and bound by ridge-lines is a *dale.* All slope lines in a hill ascend to a single peak, and all of the slope-lines in a dale descent to a single pit, respectively. Maxwell also proposed a set of numerical relations among the surface features that must be valid for an accurate surface network extracted from a smooth, differentiable surface.

In the 1960s, William Warntz rediscovered and synthesized this previous work on surface theory [52-53]. Warntz [52] also extended Maxwell's concepts by introducing *territories* which overlap a hill and a dale and, thus, bound, by two ridge lines and two course lines. He also tabulated the vergency of forces flowing down the surface to lower values: peaks, ridges, and hills have divergence; pits, courses, and dales have convergence; and passes, pales, and territories have mixed vergency. He was also the first to use the concept of a network to connect the various surface points, lines and areas into a larger entity and explicitly write about the application of the theory to non-topographic geographic surfaces. Warntz [52] also included a series of informative diagrams showing how surface networks can be recognized from a contour representation of a surface. It was Pfaltz [34], however, who first proposed the term *Surface Network* for a graph-theoretic data structure (critical points serve as nodes while the connecting ridge and course lines become edges in the graph) he designed based on surface network theory to increase computational efficiency of storage and querying of surfaces. *Surface Network* has since been appropriated to also refer to the spatial version of the surface network (as in this paper). Reeb graphs [38] and Contour

Trees [23] are other data structures similar to Pfaltz's graph-theoretic model.

2.2 Applications of surface network theory

Since surface networks abstract surface structure in a highly condensed form, they offer substantial efficiency for storage, query, selection, visualization, and communication of surface information. The computational efficiency is better if the surface network is represented as a purely topological graph, than when spatial representations of features are also needed. Still, there is substantial data abstraction even for metric surface networks. For example, in the case study presented in Section 6, a terrain surface of 1.47 million cells, covering 147 square km was abstracted by less than 500 surface network elements. Pfaltz [34] also proposed a graph-theoretic method called *homomorphic contraction* for simplifying surface networks in order to increase efficiency of storage, selection, and retrieval. The net reduction from surface network simplification could be as much as 90% according to one study of vector representations of surfaces [13].

Some important application areas that benefit are surface visualization techniques and large area terrain analysis at high resolutions. Surface networks elements have long played an important role in geomorphometry [14]. The relative frequency of surface network parts for different terrain types, and their correspondence (or lack of) to visible topographic features reveals important geomorphometric information about the terrain. More complex surface features might also be identified beginning with simpler surface network elements, as has shown to be possible for terrain surfaces [44].

More generally, many surface morphometric analyses may be performed entirely with just the surface network features, such as regional segmentation based on course and ridge line, identifying regions of high variability that may benefit from additional sampling, or finding "Very Important Points" for constructing Triangular Irregular Network (TIN) data models. As noted in [33], because of its well-defined structure, a surface network provides a way to logically reason about geometric, topological, and mereo-topological relationships between distant features observed globally on a surface. It also forms a natural hierarchy that can be exploited for scale sensitive queries and abstraction of data. Another relatively unexplored application area of surface networks is comparison of surfaces [40-41] and even tracking the morphology of a surface as it evolves in the real world or in digital animations and artificial simulations.

3. Rationale for pattern design

Ontology design patterns must be generic enough to find recurring use in diverse contexts [8]. The general approach to designing patterns is to consider a set of competency questions that experts from intended application domains could submit to the pattern [12]. The pattern should attempt to formalize only those concepts that allow those questions to be addressed. However, for designing a surface network pattern, the guiding factors were not as much competency questions but the already well-established and compact theory. Since surface network theory is not known to have been formalized as an ontology before, the goal of the GeoVoCamp workshop was to design a minimalistic, comprehensible and widely reusable pattern formalizing only those concepts outlined in the classical theory discussed in [4] and [29].

Despite a theory to guide and constrain design choices, the finalization of the pattern design (quite surprisingly) still required several iterations and multiple debates to be settled. First, the distinction between typical and uncommon use cases was critical in defining the scope of the primary pattern (SNODP). It was decided that certain uncommon possibilities can be ignored, since trying to account for them would warrant highly specialized subclasses and preclude many constraints that almost always apply to certain surface network elements from being specified. Another important choice was to declare all surface network parts to belong to only one surface network, precluding multiple surface networks (for the same surface) from sharing parts. There may be benefits to such sharing and might make multi-surface network triple datasets more compact, but specification of multi-surface network semantics has never been researched, would have made the pattern too complicated.

Interestingly, the most important design decision was made post the initial deliberations at the GeoVoCamp workshop. Since the original motivation was to share terrain surface data, which requires metric surface networks, it took the authors some time to realize the benefits of creating not one, but two patterns—one supporting only topological concepts, and the other also supporting metric space properties. Maintaining a purely topological pattern is an elegant design solution because i) the original theory was limited to only topological properties surface network features; ii) the exclusively topological model still suffices for a wide range of queries and efficient information retrieval related to the global shape of the surface [33]; iii) not requiring a metric space representation eliminates the significant overhead of extracting spatial representations of surface network features; iv) different domains will need different spatial representation and querying capabilities; and v) topological surface network datasets are quite compact, and not likely to pose problems for ontology reasoners.

Based on this decision, the primary pattern called the *Surface Network ODP* (*SNODP*) is a conceptualization of only those theoretical principles needed to create a topologically consistent surface network, with the additional capability to store surface heights for critical points so that their relative importance can be determined in some analytical contexts [56]. SNODP can be extended to support description of the metric properties of surface network elements by alignment with a spatial ontology of choice.

Metric surface networks [55] require the storage of spatial coordinates of *at least* the critical points to spatially co-register the surface network with the source surface. These points act as 'entry points' to the surface and help optimize surface information retrieval algorithms [34]. If ridge and course line locations are also stored, the surface network can be fully overlaid with the surface in the same metric space, which improves surface geometry comprehension and provides analytical insights about how well surface network elements capture the local and global shape of the surface. Consequently, a metric surface network ontology design pattern needs to incorporate a spatial ontology, logically consistent with and semantically expressive enough for the target domain. GeoSNODP is such an extension for the geospatial domain, realized by loosely aligning SNODP with W3C adopted GeoSPARQL standard [32]. GeoSNODP is well-suited for LTD goals, since both metric and topological semantics are critical to understanding terrain.

4. OWL formalization

The formalization of the primary pattern (SNODP) is presented in this section. SNODP is formally encoded using the OWL 2 Web Ontology Language (OWL 2), and available online at a resolvable URI.[3] Its complete axiomatic discussion is presented in this paper using the compact Description Logic (DL) notation. Although the semantics encoded in this pattern are based on [4, 29, 52], class names were primarily derived only from [52], since certain name modifications are more appropriate for the present day (cf. use of pit and peak, instead of Maxwell's terms summit and immit). Property names are based on descriptive phrases in the literature, but not necessarily attributable to any particular author. Fig. 2 is a schematic presentation of how the various classes relate to each other. The rest of this section discusses in detail the formalization and scope of each class.

4.1 Surface

The *Surface* class exists only to make explicit the fundamental relationship that exists between a surface and its surface networks. A surface is ontologically prior to the surface network because the former is a pre-requisite for the extraction of the latter. The surface network's component elements also completely inherit their topological and spatial configuration from the source surface. The nature of this dependency is formalized using the *embeds* property in axiom 1 to capture the idea that the locations of all the parts constituting a surface network must be a subset of the locations occupied by the surface. The *embeds* property is transitive under parthood, implying that every part of the embedded surface network must also be embedded in the surface. This is specified axiomatically using a property chain [15], a built-in functionality in OWL 2 to allow axiomatic definition of new properties by a chain of object properties—in this case *embeds* and *hasPart_directly*, where the latter property is defined in the W3C recommended best practice SimplePartWhole OWL pattern.[4] SNODP uses this small pattern to be able to model straightforward cases of part-whole mereological relations, because they are not natively supported in RDFS or OWL. Property chain reasoning for the inverse properties *embeddedIn* and *partOf_directly*‑ holds automatically in OWL 2. A limitation of using

[3] The *SurfaceNetwork* OWL pattern is available @: http://purl.org/GeoVoCamp/ontology/SurfaceNetwork

[4] The Simple Part-Whole OWL pattern is available @: http://www.w3.org/2001/sw/BestPractices/OEP/SimplePartWhole/part.owl

The documentation of this pattern is available @: http://www.w3.org/2001/sw/BestPractices/OEP/SimplePartWhole/simple-part-whole-relations-v1.5.html

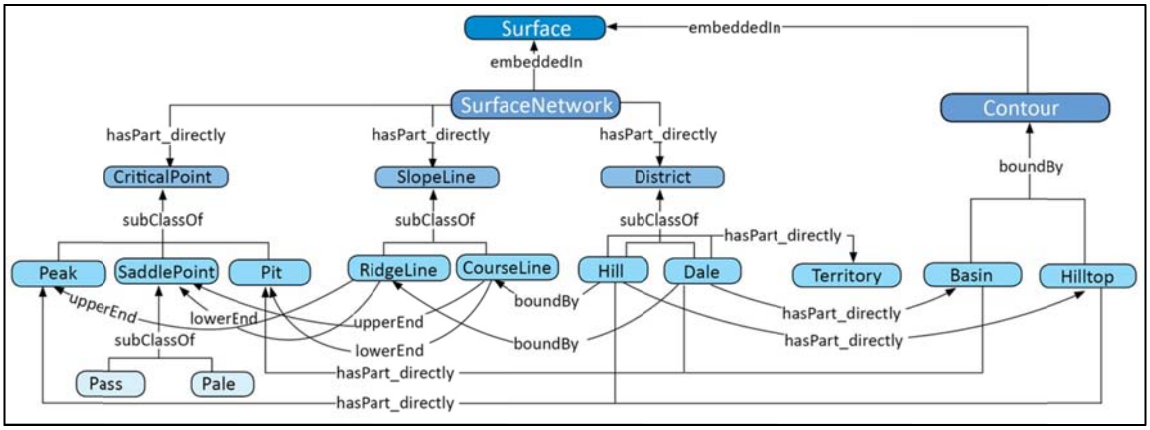

Fig. 2. Schematic representation of the Surface Network ontology design pattern.

property chaining is that reasoners must be OWL 2 compliant to infer these axiomatically specified properties.

Axiom 2 specifies that for every surface there exists a proper surface data object encoding in (non RDF format) the complete surface dataset. The *surfaceData* object property supported by the *Surface* class merely stores a link to an external resource hosting the surface dataset in its native format. If access to the external surface dataset does not need to be provided, the class can remain uninstantiated to eliminate the overhead of providing access to surface data.

$$Surface \sqsubseteq \exists embeds.SurfaceNetwork \tag{1}$$

$$Surface \sqsubseteq \exists SurfaceData.\top \tag{2}$$

Note that the *embeddedIn* property should have been restricted with a qualified cardinality of 1 to specify that the surface network and its parts are all embedded in only one surface (which is always the case). However, if the cardinality is restricted, and the *Surface* class is also not instantiated, a substitute 'dummy' object would be inferred by OWL reasoners to satisfy the cardinality constraint. Every instance would then be asserted to be embedded in that dummy object, despite such assertions not conveying any meaningful information. It was preferable to *not* specify the cardinality constraint, which preempts the vacuous assertions and also lets the *Surface* class remain uninstantiated.

4.2 Contour

Contours are often used to represent surfaces, independent of surface network elements. Similarly, it is possible to extract a surface network without explicitly creating contour representations of a surface. Axiom 3 only specifies that contours are directly embedded in exactly one source surface. But, as shown in Fig. 1, contours are needed to define basins and hilltops (see axioms 28 and 31).

$$Contour \sqsubseteq (\leq 1 embeddedIn.Surface \sqcap \geq 1 embeddedIn.Surface) \tag{3}$$

4.3 Surface Network

The *SurfaceNetwork* class is the aggregate class for all surface network classes and is related to the *Surface* class through the *embeds* and *embeddedIn* inverse properties. While axiom 1 specifies that every surface embeds at least one surface network, axiom 4 restricts every surface network to be embedded in exactly one source surface.

$$SurfaceNetwork \sqsubseteq (\leq 1 embeddedIn.Surface \sqcap \geq 1 embeddedIn.Surface) \tag{4}$$

The *SurfaceNetwork* class has six other classes as its parts that collectively model the essential semantics of a topological surface network. These classes are all mutually disjoint from each other (DL axioms are not presented below for brevity sake). As shown in Fig. 2, and specified in axioms 5a-c, the *SurfaceNetwork* class has *CriticalPoint*, *District,* and

SlopeLine as necessary (direct) parts.[5] Three other types of (indirect) parts of a surface network (basins, hilltops, and territories) may also be extracted to better explore surface shape, but their instantiation is not strictly necessary. The partonomic relationship of these three classes with the surface network is not axiomatized because they can be inferred from other axioms.

$$SurfaceNetwork \sqsubseteq \exists hasPart\_directly.CriticalPoint \quad (5a)$$

$$SurfaceNetwork \sqsubseteq \exists hasPart\_directly.District \quad (5b)$$

$$SurfaceNetwork \sqsubseteq \exists hasPart\_directly.SlopeLine \quad (5c)$$

The primary purpose of the *SurfaceNetwork* class is to help partition the collections of parts of a particular surface network, when multiple surface networks are generated and managed as part of the same resource (e.g., SPARQL graph, RDF document). Without this class, it would not be possible to distinguish which of the unique parts of a surface comprise which specific surface network. For this pattern, it is assumed that surface network parts are unique across all surface networks by default, since it makes reasoning simpler and also prevents some unintended and incorrect partonomic relationships to be inferred between parts of different surface networks. Axioms 6-8 specify this important design logic that all critical points, districts, and slope lines (including course and ridge lines) are part of exactly one surface network (and, therefore, embedded in only one surface). Although not declared explicitly, basins, hilltops and territories can be inferred to be part of only one surface network.

$$CriticalPoint \sqsubseteq (\leq 1 partOf\_directly.SurfaceNetwork \sqcap \geq 1 partOf\_directly.SurfaceNetwork) \quad (6)$$

$$District \sqsubseteq (\leq 1 partOf\_directly.SurfaceNetwork \sqcap \geq 1 partOf\_directly.SurfaceNetwork) \quad (7)$$

$$SlopeLine \sqsubseteq (\leq 1 partOf\_directly.SurfaceNetwork \sqcap \geq 1 partOf\_directly.SurfaceNetwork) \quad (8)$$

However, note that the most common use cases of SNODP will probably involve only one surface network extracted from a surface. In such cases, instantiation of the *SurfaceNetwork* class may be avoided since it will only lead to a lot of 'vacuous' assertions that *every* instantiated individual is part of a surface network, with no additional value gained. In the absence of other surface networks, such assertions are unnecessary. On the other hand, not instantiating the *SurfaceNetwork* class will also have the side-effect of disrupting the property chain needed to infer that the parts of the surface network are also embedded in the surface, which would sever the link between surface network parts and the source surface. Hence, if access to the original surface is necessary, the *SurfaceNetwork* class should always be instantiated.

4.4 Critical Points

Critical points are the most basic elements of a surface network and, in many cases, they are the only elements extracted. Merely having knowledge of critical points or even a subset of them (e.g., only peaks or pits) is sufficient in many cases. For example, topographic maps generally need to show only peaks and some passes of strategic importance; finding only the pits for a terrain surface approximated through a digital elevation model is an important step in hydrological analysis; and in [53], only peaks and saddles were needed to guide algorithms for extracting the spatial extents of topographic eminences.

The essential semantics pertaining to critical points is captured by axioms 9-10 below. The *CriticalPoint* class models the mathematical category of critical points of a surface network. The class has three subclasses: *Peak*, *Pit*, and *SaddlePoint* (axioms 9a-c). These three subclasses model, respectively, local maxima, local minima, and saddle stationary points (*i.e.*, non-extrema points where the first derivative (gradient) in all directions on a surface is zero making the tangential plane at that point parallel to the base plane of the surface). Axioms 9d-g also specify that the *CriticalPoint* class is a disjoint union of its three subclasses, since mathematically, a point on a surface can be an instance of only one type of critical point.

All *CriticalPoint* classes must also support a numeric *surfaceValue* datatype property (datatype *double*) to record surface heights as measured along an axis oriented orthogonal to the base plane domain of the surface (axiom 10). Axioms 11-12 specify that every peak is always a direct part of exactly one hill and exactly one hilltop (which is part of the same hill that the peak is part of). Similarly, axioms 13-14 specify that every pit is always a direct part of exactly one dale and exactly one basin (which is part of the same dale that the pit is part of).

[5] As explained in the documentation of the SimplePartWhole pattern, *hasPart* is a transitive property useful for identifying all parts of an entity or its constituting parts, while the non-transitive *hasPart_directly* is a way of identifying only the "next-level" breakdown of parts of an entity or its constituting parts.

$$Peak \sqsubseteq CriticalPoint \quad (9a)$$

$$Pit \sqsubseteq CriticalPoint \quad (9b)$$

$$SaddlePoint \sqsubseteq CriticalPoint \quad (9c)$$

$$CriticalPoint \sqsubseteq Peak \sqcup Pit \sqcup SaddlePoint \quad (9d)$$

$$Peak \sqcap Pit \sqsubseteq \bot \quad (9e)$$

$$Peak \sqcap SaddlePoint \sqsubseteq \bot \quad (9f)$$

$$Pit \sqcap SaddlePoint \sqsubseteq \bot \quad (9g)$$

$$CriticalPoint \sqsubseteq (\leq 1 SurfaceValue.double \sqcap \geq 1 SurfaceValue.double) \quad (10)$$

$$Peak \sqsubseteq (\leq 1 partOf\_directly.Hill \sqcap \geq 1 partOf\_directly.Hill) \quad (11)$$

$$Peak \sqsubseteq (\leq 1 partOf\_directly.Hilltop \sqcap \geq 1 partOf\_directly.Hilltop) \quad (12)$$

$$Pit \sqsubseteq (\leq 1 partOf\_directly.Dale \sqcap \geq 1 partOf\_directly.Dale) \quad (13)$$

$$Pit \sqsubseteq (\leq 1 partOf\_directly.Basin \sqcap \geq 1 partOf\_directly.Basin) \quad (14)$$

The *SaddlePoint* class is a disjoint union of two subclasses, *Pass* and *Pale* (axioms 15a-d). Authors have used the term *pass* in two senses: i) to refer to *any* saddle point, and ii) the subset of saddle points that are the lowest point between two peaks. This ambiguity is addressed in this pattern, by using *SaddlePoint* to refer all saddle points. A saddle point is classified as a *Pass* if it is the lowest point on a ridge line connecting two peaks, or as a *Pale* otherwise, which implies it must be the highest point on a course line connecting two pits. Axioms 16a-b specify additionally that saddle points are the lower end of exactly two ridge lines, and upper end of exactly two course lines meeting at the saddle point. The meeting of more than two ridge lines and two course lines is generally not a common occurrence and such special saddle points may be (imperfectly) accommodated in a traditional surface network as a combination of multiple 'normal' saddle points.

$$Pass \sqsubseteq SaddlePoint \quad (15a)$$

$$Pale \sqsubseteq SaddlePoint \quad (15b)$$

$$SaddlePoint \sqsubseteq Pass \sqcup Pale \quad (15c)$$

$$Pale \sqcap Pass \sqsubseteq \bot \quad (15d)$$

$$SaddlePoint \sqsubseteq (\leq 2 lowerEndOf.RidgeLine \sqcap \geq 2 lowerEndOf.RidgeLine) \quad (16a)$$

$$SaddlePoint \sqsubseteq (\leq 2 upperEndOf.CourseLine \sqcap \geq 2 upperEndOf.CourseLine) \quad (16b)$$

4.5 Slope Lines

The critical points of a surface network are connected via slope lines, which run up and down slopes perpendicular to contour lines. Topological connections between critical points and slope lines are modeled through two properties: *upperEnd* and *lowerEnd*, where up and down directions correspond to the direction of convexities (maxima) and concavities (minima), respectively, and determined by the basal plane of the surface. The range of the two properties must be some *CriticalPoint*. Axioms 17a-b specify that a slope line has either one peak or one saddle point at its upper end, and either one pit or one saddle point at its lower end, to account for the special cases of ridge and course lines which do not run from peak to pit. Axioms 18a-c establish that *CourseLine* and *RidgeLine* are two disjoint subclasses of *SlopeLine*. Axioms 19a-b extend the more generalized axioms 17a-b to clarify that course lines are slope lines that can only have a saddle point at the upper end and only a pit at the lower end. Similarly, axioms 20a-b clarify that ridge lines must have a peak at the upper end and a saddle point at the lower end. Thus, course lines never extend above saddle points toward peaks, and ridge lines never extend saddle points toward pits. Ridge and course lines are critical shape defining slope lines, whereas other slope lines do not signify anything unique about surface shape, and are normally not even extracted—hence, for simplicity there is no special subclass defined for such slope lines.

$$SlopeLine \sqsubseteq ((\leq 1 upperEnd.Peak \sqcap \geq 1 upperEnd.Peak) \sqcup (\leq 1 upperEnd.SaddlePoint \sqcap \geq 1 upperEnd.SaddlePoint)) \quad (17a)$$

$$SlopeLine \sqsubseteq ((\leq 1 lowerEnd.Pit \sqcap \geq 1 lowerEnd.Pit) \sqcup (\leq 1 lowerEnd.SaddlePoint \sqcap \geq 1 lowerEnd.SaddlePoint)) \quad (17b)$$

$$CourseLine \sqsubseteq SlopeLine \quad (18a)$$

$$RidgeLine \sqsubseteq SlopeLine \quad (18b)$$

$$CourseLine \sqcap RidgeLine \sqsubseteq \bot \quad (18c)$$

$$CourseLine \sqsubseteq (\leq 1 upperEnd.SaddlePoint \sqcap \geq 1 upperEnd.SaddlePoint) \quad (19a)$$

$$CourseLine \sqsubseteq (\leq 1 lowerEnd.Pit \sqcap \geq 1 lowerEnd.Pit) \quad (19b)$$

$$RidgeLine \sqsubseteq (\leq 1 upperEnd.Peak \sqcap \geq 1 upperEnd.Peak) \quad (20a)$$

$$RidgeLine \sqsubseteq (\leq 1 lowerEnd.SaddlePoint \sqcap \geq 1 lowerEnd.SaddlePoint) \quad (20b)$$

4.6 District

The *District* class is a superclass created specifically for SNODP to cover the concepts of both hills and dales, which are areal partitions of the surface by the network of course or ridge lines, respectively. More specifically, Axioms 21a-b specify that a district is bound by either only course lines or only ridge lines, and no other type of surface network entity, and there must be at least one bounding course or ridge line for a district to exist. The next set of axioms 22a-d define the *District* class as a disjoint union of *Hill* and *Dale* subclasses, clarifying that the scope of the *District* class is strictly limited to only dales and hills, and no other type of areal parts of surface networks features (e.g., basin, hilltop, territory). Axioms 23a-b state that dales are districts bound by only and at least one (typically more) ridge line, while axioms 24a-b specify that hills are bound by only and at least one (typically more) course line. Note that the complete sets of hill instances or dale instances exhaustively partition a surface, independent of each other; so every hill instance must spatially overlap with a dale instance and vice versa.

$$District \sqsubseteq (\forall boundBy.CourseLine \sqcup \forall boundBy.RidgeLine) \quad (21a)$$

$$District \sqsubseteq (\exists boundBy.CourseLine \sqcup \exists boundBy.RidgeLine) \quad (21b)$$

$$Dale \sqsubseteq District \quad (22a)$$

$$Hill \sqsubseteq District \quad (22b)$$

$$District \sqsubseteq Dale \sqcup Hill \quad (22c)$$

$$Dale \sqcap Hill \sqsubseteq \bot \quad (22d)$$

$$Dale \sqsubseteq \forall boundBy.RidgeLine \quad (23a)$$

$$Dale \sqsubseteq \exists boundBy.RidgeLine \quad (23b)$$

$$Hill \sqsubseteq \forall boundBy.CourseLine \quad (24a)$$

$$Hill \sqsubseteq \exists boundBy.CourseLine \quad (24b)$$

An intuitive interpretation of hills and dales is necessary to appreciate their importance in describing the shape of a surface. For a terrain surface, a dale would correspond to a drainage basin that is of critical importance in terrain and hydrologic analysis and. Hills can be imagined as the (often) convex regions surrounding a peak and bound by valleys or lines with negative curvature (corresponding to course lines). Another way to conceptualize a hill or dale is the union of all slope lines converging at the same peak or pit, respectively, with ridge lines acting as boundaries of dales and course lines as boundaries of hills. This leads to axioms 25-28. Every dale has exactly one pit and one basin, and every hill has exactly one peak and one hilltop as a direct part.

$$Dale \sqsubseteq (\leq 1 hasPart\_directly.Pit \sqcap \geq 1 hasPart\_directly.Pit) \quad (25)$$

$$Dale \sqsubseteq (\leq 1 hasPart\_directly.Basin \sqcap \geq 1 hasPart\_directly.Basin) \quad (26)$$

$$Hill \sqsubseteq (\leq 1 hasPart\_directly.Peak \sqcap \geq 1 hasPart\_directly.Peak) \quad (27)$$

$$Hill \sqsubseteq (\leq 1 hasPart\_directly.Hilltop \sqcap \geq 1 hasPart\_directly.Hilltop) \quad (28)$$

4.7 Non-Critical Elements: Basin, Hilltop, and Territory

Basin, *Hilltop* and *Territory* classes are not absolutely essential to the definition of a surface network, but are special types of regions on a surface that can be defined only in reference to a combination of critical points, slope lines, and districts. These secondary types of regions are not explicitly defined in the surface network literature, but loose references to similar features are found occasionally. These features are defined formally for SNODP because they capture important surface shape parts that are expected to be relevant in several types of use cases, as discussed below.

4.1.1. Basin

Intuitively, a basin is the low lying area around a pit. More formally, it should be conceptualized as the area around a pit fully enclosed by the highest contour that meets the lowest pale connected directly to a pit via a course line. The pale is the highest point between the pit and another pit, and the bounding contour separates the low-lying basin from the completely higher land enclosing it. Basins are useful for analyzing regions of localized low values in a surface. The closest analogue of a basin in the real world is a physical depression in the surface of the earth (or any other planet), with its upper limit being defined by the level of the lowest outlet (pour point) through which water would flow out of the depression (imagine lake or pond flowing over on to surrounding land). More generally, for any surface, basins serve as objectively defined areal extensions of critical points. Extending the concept of the minima critical point to a minima critical region (the basin) incorporates important structural information about a surface's shape around the pit that would otherwise be unavailable if one were to look at only the points of minima. For example, while analyzing density surfaces of personal income or industrial production, the basin would highlight low-performing regions of concern, while basin shape and orientation could provide a unique perspective of each low performing region. A basin thus provides additional "context" to the pit.

Axioms 28-30 formalize only a minimal set of basin semantics that are appropriate for the purely topological SNODP. Complete specification of the spatial semantics of the basin's relationship to the contour, pale and the surrounding enclosing area would require far too many sophisticated spatial concepts, and must be attempted in an ontology of metric surface networks. Axiom 28 only specifies that the basin is bound by exactly one contour. Axiom 29 specifies that a basin must have exactly one pit as a direct part, while axiom 30 species that every basin is part of only one dale. The basin can, therefore, be also conceptualized as the lowest part of a dale between the pit and the lowest pale within the dale.

$$\mathit{Basin} \sqsubseteq (\geq 1 \mathit{boundBy.Contour} \sqcap \geq 1 \mathit{boundBy.Contour}) \tag{28}$$

$$\mathit{Basin} \sqsubseteq (\leq 1 \mathit{hasPart\_directly.Pit} \sqcap \geq 1 \mathit{hasPart\_directly.Pit}) \tag{29}$$

$$\mathit{Basin} \sqsubseteq (\leq 1 \mathit{partOf\_directly.Dale} \sqcap \geq 1 \mathit{partOf\_directly.Dale}) \tag{30}$$

4.1.2. Hilltop

The concept of a hilltop is quite similar to that of a basin, if the perspective of observing the surface is shifted from 'looking down' at the pit to 'looking up' to a peak. A hilltop is the area around a peak and bound by the highest enclosing contour that meets the highest pass connected to the peak through a ridge line. Similar to the basin, there are analytical benefits of extending a peak with an objectively delineated critical maxima region. For the physical terrain of the earth, a hilltop would correspond to the area between a mountain peak and the highest mountain pass connected to the peak. For economic surfaces as for income or industrial production, hilltops represent areas of good performance standing out appreciably from their surrounding locations. Hilltop shape and orientation analysis has the potential to explain the reasons better than mere peak analysis. Axioms 31-33 formalize the basic topological shape semantics of the hilltop, mirroring and having similar interpretations as the axioms for the *Basin* class.

$$\mathit{Hilltop} \sqsubseteq (\geq 1 \mathit{boundBy.Contour} \sqcap \geq 1 \mathit{boundBy.Contour}) \tag{31}$$

$$\mathit{Hilltop} \sqsubseteq (\leq 1 \mathit{hasPart\_directly.Peak} \sqcap \geq 1 \mathit{hasPart\_directly.Peak}) \tag{32}$$

$$\mathit{Hilltop} \sqsubseteq (\leq 1 \mathit{partOf\_directly.Hill} \sqcap \geq 1 \mathit{partOf\_directly.Hill}) \tag{33}$$

4.1.3. Territory

Since hills and dales both exhaustively partition the surface into regions, their instances always must overlap with each other spatially on the surface. The semantics of these overlapping areas are formalized through the *Territory* class in SNODP. As outlined by axioms 33a-c, a territory needs to be bound exactly by two course and ridge lines simultaneously, and axioms 34a-b further specify that a territory can be a shared area only between one hill and dale exactly, and no more.

$$\mathit{Territory} \sqsubseteq (\exists \mathit{boundBy.CourseLine} \sqcap \exists \mathit{boundBy.RidgeLine}) \tag{33a}$$

$$\mathit{Territory} \sqsubseteq (\leq 2 \mathit{boundBy.CourseLine} \sqcap \geq 2 \mathit{boundBy.CourseLine}) \tag{33b}$$

$$\mathit{Territory} \sqsubseteq (\leq 2 \mathit{boundBy.RidgeLine} \sqcap \geq 2 \mathit{boundBy.RidgeLine}) \tag{33c}$$

$$\mathit{Territory} \sqsubseteq (\leq 1 \mathit{partOf\_directly.Hill} \sqcap \geq 1 \mathit{partOf\_directly.Hill}) \tag{34a}$$

$$\mathit{Territory} \sqsubseteq (\leq 1 \mathit{partOf\_directly.Dale} \sqcap \geq 1 \mathit{partOf\_directly.Dale}) \tag{34b}$$

5. Extending SNODP for the geospatial domain

SNODP does not include spatial semantics, which would have limited the applicability of the pattern, since different contexts need different formalizations of spatial semantics. SNODP should be interpreted as a template ontology pattern that defines only the fundamental topology semantics of a surface network, with no commitment to the additional specification of spatial semantics for metric surface networks. An extension of SNODP for the geospatial domain, in general, is discussed in this section, since most use cases arise from geospatial analysis and visualization needs. The same extension pattern is also well suited for semantic annotation of terrain surface networks.

5.1 Extending SNODP with GeoSPARQL

SNODP already covers almost all the required semantics of surface networks, so the extension for the geospatial domain only needs to provide a way to describe the location and a limited set of metric properties and relationships (e.g., distance, length, area) of surface network elements. For compatibility with the Semantic Web, locations semantics should be defined using an ontology that allows serialization of all parts' locations as RDF triples. The Open Geospatial Consortium (OGC) sponsored a standard called GeoSPARQL, which extends SPARQL, a W3C recommended RDF query language, with geospatial information representation and retrieval capabilities on the Semantic Web [32]. GeoSPARQL is based on existing OGC standards and also addresses several limitations with previously proposed geospatial vocabularies (see [1] for an extensive review). GeoSPARQL supports a simple ontology for representing geospatial data semantics, which can be attached to any other ontology that needs to describe basic geometric properties of spatial entities. GeoSPARQL ontology is not a formal ontology of the geospatial domain, but is still robust enough to support representation and querying of most common Euclidean geometric representations of geospatial data and also simple enough for Linked Data. There are several properties of spatial entities that GeoSPARQL does not support yet (including semantics of basic spatial properties such as length, area or volume). Nonetheless, for the modest technical goal of extending SNODP with geospatial capabilities, it is currently the best publicly available solution.

5.1.1 GeoSPARQL Classes and Properties

A brief review of the GeoSPARQL ontology is provided in this section before discussing alignment with SNODP in the next section. The GeoSPARQL ontology can be downloaded and examined in an ontology editor such as Protégé. [6] The primary class in GeoSPARQL is *geo:SpatialObject* which represents all spatial entities, and subsumes two subclasses: *geo:Feature* and *geo:Geometry*. These are declared to be disjoint so that geospatial entities can be conceptualized independent of their geometric representations. A *geo:Feature* is an abstraction of any entity which can have a real world location. No further specialization of this class is entailed since that is left to domain ontologies. The *hasGeometry* object property, which has *geo:Feature* as its domain and *geo:Geometry* as its range, links all *geo:Feature*s to their geometric representations. The *geo:Geometry* class subsumes all the geometry classes typically needed for representing the spatial extension of geospatial entities. A *geo:Feature* can have multiple *geo:Geometry*s to support different reasoning contexts, and one of them (usually the most detailed) may also be declared as the *geo:defaultGeometry* for typical use cases.

For RDF compatibility, the spatial location of *geo:Geometry* must be converted from traditional spatial database storage formats and serialized as a geometric literal, which can be based either on the Well-Known Text (WKT) [7] or the Geographic Markup Language (GML) [8] vector geometry representation standards. Unlike many other geospatial standards, GeoSPARQL supports multiple coordinate reference systems (CRSs) as defined by the European Petroleum Survey Group (EPSG) system. [9] The *geo:Geometry* class further depends on the *hasSerialization* data property, which has two subproperties: *geo:asWKT* and *geo:asGML*, to link to the appropriate WKT or GML geometric literal representation, respectively. Values for these properties use the *geo:wktLiteral* and *geo:gmlLiteral* data types respectively.

5.1.2 Geospatial Surface Network ODP

Fig. 3 schematizes the Geospatial Surface Network ODP as derived by alignment of SNODP with GeoSPARQL ontology. The OWL formalization of GeoSNODP is available online.[10] The rationale for deciding how to align SNODP with GeoSPARQL is discussed below.

[6] http://www.opengis.net/ont/geosparql
[7] WKT was originally specified in Simple Feature Access (Part 1: Common Architecture), an OGC® and ISO standard (19125).
[8] http://www.opengeospatial.org/standards/gml
[9] http://www.epsg-registry.org
[10] The *GeospatialSurfaceNetwork* OWL pattern is available @: http://purl.org/GeoVoCamp/ontology/GeospatialSurfaceNetwork

Any geospatial entity declared in other ontologies can be subsumed by *geo:Feature* to inherit geospatial properties and its location can be declared using the *geo:Geometry* subclasses. Because surface network entities are mathematical (points, lines, areas) and not real world entities, it might seem appropriate to declare them as subclasses of *geo:Geometry* in GeoSPARQL. However, that would limit the representation of a surface network element to only a *particular* geometric representation, precluding its representation at different levels of detail with multiple geometries, *all* linked via its *hasGeometry* property to the same *geo:Feature* (and to each other). More importantly, such a choice would also be conceptually flawed since surface network elements are not *mere* geometric shapes; they also have specific spatial and topological properties, and there are many other rules that apply to them. Thus, surface network elements should not be subclasses of *geo:Geometry*, and must be subsumed by *geo:Feature*. Accordingly, as shown in Fig. 3, the GeoSNODP classes: *CriticalPoint*, *SlopeLine*, *District*, and *Contour* are declared subclasses of *geo:Feature*. Their subclasses and parts automatically inherit *geo:Feature* properties as well. All properties from SNODP are retained. The *geo:Geometry* classes can be used for instantiating the location and shape of all surface network elements in GeoSNODP—an option that is not available in SNODP. Note that the *SurfaceNetwork* class should not be aligned with *geo:Feature* since only instances of its contained classes can have spatial representation, not the network as a whole.

GeoSNODP supports *orthometricHeight* as a specialized sub-property of *surfaceValue*, primarily to make users aware of a certain constraint on how terrain surface heights should be measured. For extracting surface network geometry, it is crucial that all surface heights be measured exactly in the direction perpendicular to the base plane of the surface—i.e., the surface should not be 'tilted' from its original spatial orientation. Enforcing all heights to be orthometric is an indirect method of specifying the correct vertical orientation of the surface in geographic space. An orientation change of the surface will cause a different set of surface network elements to be extracted. For example, if the terrain surface is not constrained to be oriented in the gravitational "up" direction (by using orthometric elevations), the mathematically extracted shape elements will not be guaranteed to match in type or overlap properly with observed terrain shapes. For example, GPS elevations are measured with respect to the WGS84 ellipsoid, and the surface realized from those elevations will not yield orthometric heights. For terrain surfaces, elevation must be measured only with respect to a level surface (e.g., Geoid or mean sea level) perpendicular to the gravity vector [29].

6. Applying GeoSNODP to terrain surfaces

6.1. GeoSNODP as a 'core' terrain ontology

GeoSNODP can be used for any type of geospatial surface network, but the primary use of this pattern will be for terrain surfaces. When surface network elements are extracted from a terrain surface and analyzed in geographic space, they have clear correspondence to observable terrain features. The nature of these correspondences is outlined below.

Peaks are universally known topographic features, while many morphologically salient passes are recognized, at least, by some groups, as part of paths from one mountain to another. Hilltops may not have an exact correspondence always, but they often include the prominent summit area around peaks. Bodies of standing water often occupy the low lying depressions that would be basins in surface networks. The lowest point within each depression would correspond to a pit in the surface network. If there is a water body in the depression, and if it is full to have an outlet, the point of overflow is a "natural" gateway from one basin to another—and idealized as a pale in the surface network. The upper limit or rim of the depression is the contour line passing through that pale. Course lines run through the watercourses which are locations over which water collects and flows under influence of gravity, often as streams and rivers. Drainage basins are perceived more for their function than morphology—they are units of land that drain water 'together' into watercourses that also lie within the extent of these basins. Drainage basins are equivalent to surface network dales, and are separated by drainage divides, which would correspond to ridge lines. People also recognize mountain sides and valley walls as shared areas—these are territories in a surface network. Hills represent land parcels partitioned by watercourses. Hills do not correspond to functional spatial units for explaining a spatial process, and often not even recognizable as a whole due to a lack of well-defined morphology. In terrain with high relief, they may correspond approximately to areas occupied by mountains and hills.

GeoSNODP is, thus, well-positioned to serve as the 'core' terrain ontology since it covers most of the

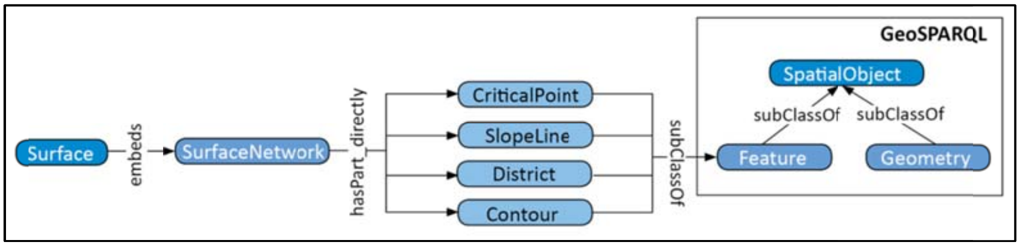

Fig. 3. Schematic representation of the top level classes of Geospatial SNODP.

basic concepts needed for terrain ontology. This realization led to the organization of another SOCoP organized GeoVoCamp workshop[11] in November 2013 for designing a pattern for surface water feature types using the surface network pattern. The pattern ultimately ended up being independently designed, because surface network feature definitions were found too restrictive to account for all types of surface water features. Complete details of the Surface Water pattern and why SNODP classes were found inadequate are available in another publication [45]. The general understanding currently is that SNODP and GeoSNODP will serve as the default ontology of terrain that can be used in the absence of or to complement the more targeted topographic ontologies (e.g., the Surface Water pattern). For example, the Surface Water pattern classes cannot account for overland flow not contained in channels, but such flow semantics might be captured with extensions to slope lines in SNODP. However, there are obvious overlaps and complementarity between concepts defined in the two patterns, and, another GeoVoCamp is being planned to align and/or integrate the GeoSNODP and Surface Water pattern that would provide a clear logical framework for using concepts from both patterns to complement each other, in a way that would not cause logical inconsitencies.

GeoSNODP will need to be complemented with other terrain ontologies because some terrain features and relationships will always remain unaccounted for in the traditional surface network theory. For example, localized spurs and ridge networks often do not extend between a peak and a pass, or stream channels or gullies may not extend up to a pass on a ridgeline, and will fail to be represented in a surface network. Conversely, many ridges and course lines in a surface network may have no noticeable terrain expression if the terrain is near-planar. Watercourses are mostly monotonically connected terrain features because their morphology is reinforced over time with sustained hydrological flow action. In comparison, ridges are more difficult to detect as topologically continuous ridge lines because no such process reinforces their morphology along their length.

6.2. Case Study

In this section, an LTD motivated case study is presented to show how parts of a surface network, extracted for a terrain surface, can be annotated using GeoSNODP classes. Fig. 4 maps the Presidential Range mountain range in the White Mountains national forest, in New Hampshire, USA. The famous peaks of the range are labeled for reference. The 10 meter resolution raster digital elevation model (DEM) (elevation measured in meters with least count of 1/10th meter) for this study area was downloaded from the USGS National Map information system. Custom software developed using the Terralib[12] spatiotemporal library was then used to process the elevation dataset and extract surface network parts.

6.2.1. Extracting terrain surface network features

The original terrain surface had too much short-ranged "noise", which caused an excessively high number and unrealistic critical points and lines to be extracted. This is a common problem in analyzing even moderately high resolution DEMs for surface networks. The DEM was, therefore, smoothed five times using the simple mean smoothing operator, since the theory is also intended for smooth surfaces. Smoothing decreased the total number of critical points almost four fold but no visually detectable changes to the surface relief were observable. Next, peaks, pits, saddle points, ridge lines and course lines were extracted using simple local morphometric rules applied to every cell in the DEM. Peaks are cells which have the highest cell values, whereas pits are cells with the lowest cell value in a surrounding

[11] http://vocamp.org/wiki/GeoVoCampDC2013

[12] http://www.terralib.org

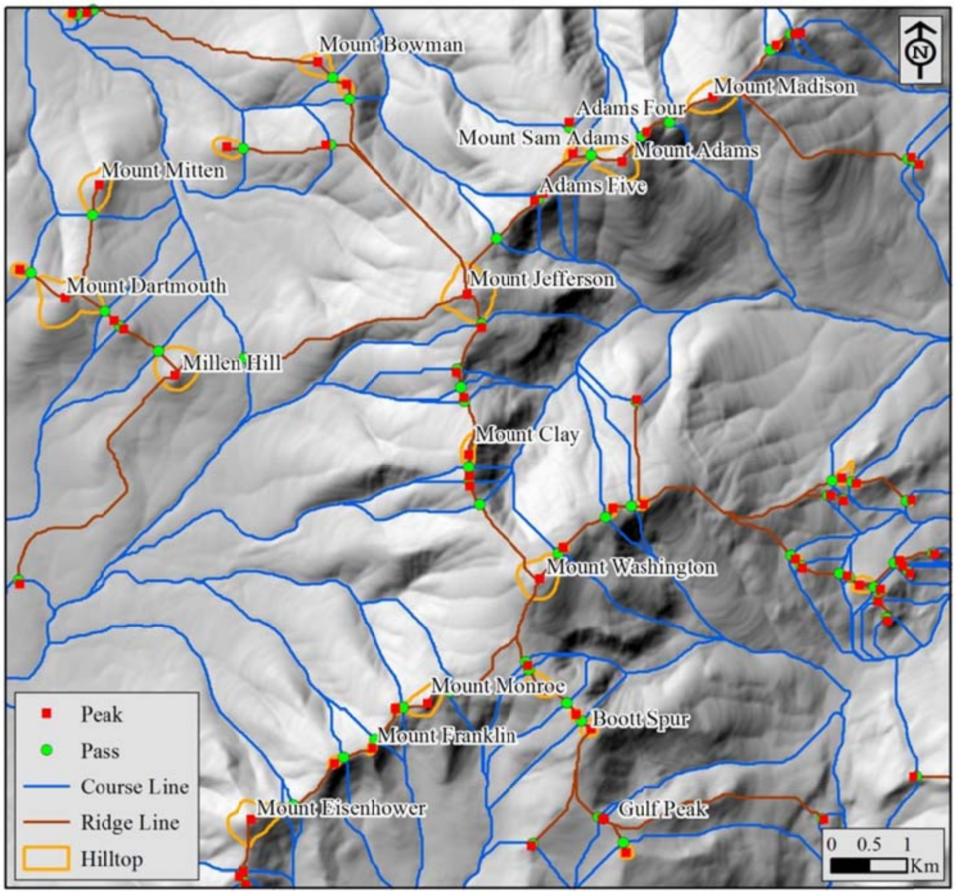

Fig. 4. A map of surface Network features overlaid on a terrain surface with coverage of the Presidential Range in NH, USA.

neighborhood, while saddles are cells with at least two uplsope and two downslope neighbors. Ridge and course lines were traced by sequentially connecting the steepest upslope and downslope neighboring cell, respectively, until a peak or a pit or the study area edge was encountered (there were no flat cells with all equal elevation neighbors).

sThe study area is not known to have any notable lake or pond, and, in any case, digital elevation models force water filled basins (e.g. lakes) to have a single elevation, making them effectively flat regions in the DEM. There are no such regions known to exist in this area. There were several single cell pits, but such pits are well known to be spurious artifacts of data processing, and were, therefore, 'filled'. The filling method used was simple in that involved raising the pit cell elevation to marginally higher that of the highest downslope neighbor, so that the cell admits a downslope path. This and many other sophisticated methods for filing pits and depressions and extended flat areas are used in hydrologic terrain analysis. The entire study area was subsequently assumed to have a universal pit surrounding it where all course lines terminate. Basins and pales cannot be identified because no pits exist in the study area.

Due to a lack of pits and flat areas, course lines were topologically terminated only at the edge, which allowed easy demarcation of hills as topologically closed polygons. These hill polygons are not shown explicitly in Fig. 4 but can be inferred as regions enclosed between the (blue) course lines. On the contrary, ridge lines ridge lines were not as dense and did not reach the study area edge. Consequently, dales could not be demarcated due to a lack of closed polygons. While this limitation is not a serious concern for this illustrative case study, the authors are exploring more sophisticated surface network extraction algorithms to improve both ridge and course line topology so that hills and dales can be demarcated properly.

For such reasons, Fig. 4 maps only a subset of possible surface network features for this study area: peaks, passes, ridge and course line starting from every pass, and a hill and hilltop for every peak. There are 73 peaks, hills and hilltops, 72 passes (pass count must always be one less than peak count), 144 ridge and 144 course lines (two per pass) that approximate the terrain of this study area. As is evident from the map, all major mountain peaks, mountain passes, stream channels, and ridge tops of the study area are mirrored by corresponding features in the surface network. The ridge lines successfully connect all of the Presidential Range's well known mountain peaks. As expected, minor channels and ridges/spurs do not have representation in the surface network, because of the restrictive way ridge and course lines are defined in the original theory. However, it can still be said with confidence that this particular surface network abstracts terrain shape quite satisfactorily, keeping in mind certain theoretical limitations.

6.2.2. Using GeoSNODP as domain ontology

In spatial analysis and mapping contexts, a clear benefit of GeoSNODP is that the pattern serves as a general domain reference for people to understand the semantics of the extracted surface network features in relation to each other and the underlying surface, since such knowledge is not captured systematically by database schemas or, least of all, map legends. The availability of the patterns, with explicit support for basic spatial semantics, is clearly a useful contribution to the field of topographic mapping and geomorphometry. When surface networks are used to extract higher order landforms, the two surface network patterns will serve to guide the design of methods of landform detection and delineation.

A major benefit of the GeoSNODP pattern is advancing the nascent vision of Linked Topographic Data. It is already clear from the review of surface network theory, and the case study results mapped in Fig. 4, that geospatial surface networks can be useful abstractions of terrain surfaces. All that needs to be shown through this case study is how surface network features can act as 'representatives' of the surface on the Semantic Web. This required the conversion of the entire surface network dataset from the native binary shapefile format into the text based RDF triples. A relatively small (< 250 lines of new code) Java program was written, reusing two external libraries: Jena[13] for creating the RDF model, and GeoTools[14] for processing binary shapefiles. Instances of each surface network feature type were grouped in a separate shapefile, and assigned a unique ID and attribute information for semantic annotation. For every shapefile, every instance was processed sequentially by the program to create a unique URI for the Semantic Web and to convert the associated spatial and attribute information for that instance into a set of RDF statements based on GeoSNODP semantics. The resulting RDF resource containing all surface network semantics and spatial coordinates of features (in WGS84 datum latitude/longitude format) is available online as a Linked Data resource.[15] The original surface dataset is also available online[16] as an ESRI ASCII text file (well-known GIS raster interchange data format). Note that the *Surface* class had to be instantiated for this surface network ontology, so that its *surfaceDataset* property can be assigned a string literal whose value is the URL of the ASCII file containing the source surface dataset.

The RDF triples generated can be queried using GeoSPARQL, since it not only provides the semantics for spatial representation, but also semantic querying of geospatial data on the Semantic Web. A Parliament™[17] triple store was populated with the RDF triples for testing a few sample GeSPARQL queries. Listed below are five queries (in compact natural language form). For illustration purposes, the GeoSPARQL query implementation of the first query listed below is shown in Fig. 5. The complete GeoSPARQL syntax of all these five queries and the results is available online as a text file.[18]

Q1. Find the peak associated with Hilltop 46 and the peak's geometry.
Q2. Find all critical points and their type within the specified bounding box.
Q3. Find all of the ridge lines which intersect the specified bounding box.
Q4. Find all of the slope lines that touch CourseLine ID900258 and their types.
Q5. Find peaks with passes at least 5 km away or at least 500 m lower than the peak.

[13] http://jena.apache.org

[14] http://www.geotools.org

[15] Surface network dataset in RDF format is available @: http://purl.org/GeoVoCamp/ontology/GeospatialSurfaceNetwork-PresRange2014Example.ttl

[16] Surface dataset in ESRI ASCII format is available @: http://purl.org/GeoVoCamp/ontology/Surface-PresRange2014Example.txt

[17] http://parliament.semwebcentral.org

[18] http://purl.org/geovocamp/ontology/GeospatialSurfaceNetwork-PresRange2014Example-GeoSPARQLQueries.txt

These queries need not be understood only in the context of just surface networks. Queries such as these also help reveal important summary information about the landforms of an area, without needing to first develop a specialized ontology of landforms. It is obvious from Fig. 4 that the prominent mountain summits of the Presidential Range are well represented by surface network peaks, and ridge tops joining them by ridgelines. Important mountain passes between peaks are abstracted by surface network passes. The major stream channels correspond well to course lines. Hence, even without the overhead of designing other patterns (e.g., the Surface Water pattern), it still is possible to query for the primary stream channels by querying about their surrogate course lines instead. Similarly, hill, hilltop geometry, and peak-pass separation provide important information about the topographic eminences in the areas as discussed in [46]. As shown in [42], watershed and mountain hierarchies can also be derived from terrain surface networks. If surface network databases are combined with gazetteers containing geocoded toponyms, queries about named streams, rivers, basins, lakes, hills, mountains, ranges, passes can also become possible. However, as noted earlier, surface networks abstract only the most important shape parts and their focus on topology and shape alone is not sufficient to capture all important semantics about landforms. There will always be a benefit to designing more specialized terrain ontology patterns to complement GeoSNODP.

Query: *"Find the peak for Hilltop 46 and its geometry."*

```
SELECT DISTINCT
?peak ?wkt
WHERE {
  data:IDHilltop.46 spw:hasPart ?peak .
  ?peak   a sn:Peak;
    geo:hasGeometry ?geo .
  ?geo geo:asWKT ?wkt .
}
```

Result:
Peak:http://purl.org/GeoVoCamp/ontology/GeospatialSurfaceNetwork-PresRange2014Example.ttl#ID100045
wkt:"POINT(-71.2432897423211 44.27319857118631)"^^<http://www.opengis.net/ont/geosparql#wktLiteral>

Fig. 5. A sample GeoSPARQL query and returned result. Prefixes (*geo*, *spw*, *sn*, and *data*) were defined for the full query, but not shown here for lack of space.

7. Integration with other ontologies

It is critical to remember that unlike physical road, river or blood vessel networks, the surface network is an *abstract*, *mathematical representation* just like its source surface. Surfaces may represent tangible physical surfaces (e.g., earth' crustal surface, earth's gravitational (Geoidal) surface, exterior of an animal body) or abstract surfaces in mathematical space (e.g., surfaces of: population density, crime potential, simulated terrain, and grayscale images). Even in the case of a physical surface (e.g., the earth's surface), surface network features should not be assumed to be observable features of the real world surface (e.g., peaks, passes, ridge tops, valleys). Instead, the correct interpretation is to always interpret surface network elements as mathematical entities, extracted from mathematically defined surfaces, which are simplified 2-D models of the real world physical surface. This will make it easier to understand the semantic gap between real shape features of the physical surface and those captured by surface networks.

Such an interpretation of a surface network cannot be specified in an ontology pattern easily. This is an example of why it is often beneficial to align ontology patterns with the philosophically motivated foundational ontologies such as DOLCE [28], BFO [11, 47] or SUMO [31] and restrict, as much as possible, the possible interpretations of the classes and relations defined in the pattern. For example, based on the discussion above, in SUMO, a surface network element would be declared explicitly as an *Abstract* object. In BFO, critical points, lines and areas could be declared as zero, one, or two dimensional *spatial region* entities, respectively, but only if "*spatial region*" covers not just the physical space but also abstract mathematical spaces. In DOLCE, surface network elements should probably be defined as *Abstract* entities, although one might argue that if a particular surface network's elements correspond to physical entities, as for terrain surfaces, the surface network may be better interpreted as a type of *Mental Objects,* which are *Non-Physical Endurant*, but not *Abstract* entities. After much consideration, it was concluded that none of the upper level can adequately capture the essential meta-level semantics that are needed to explain how SNODP and GeoSNODP should be interpreted in general. Also, a common limitation of these foundational ontologies is that their formalization of space and time is quite generic and not ideal for expanding the scope of GeoSNODP. Thus, the benefits of aligning the patterns to any foundational ontology would be minimal and may even restrict the intended interpretation.

A better solution, again, instead of awaiting an appropriate grand unifying ontology, would be to design smaller reaching ontology patterns. Recently *Descartes-Core* was proposed at one of the GeoVocamps as a community-wide collection of geo-ontology patterns and vocabularies, best-practice guides, examples and case studies, software and services. [19] Hopefully, this effort will yield ontology patterns that can benefit patterns such as those presented here. There are three foundational spatial patterns that should greatly benefit surface network patterns. The most beneficial would be the availability of an ontology pattern for 2D fields or surfaces. That would eliminate the need for the ad-hoc *Surface* class in NODP and empower users with semantic reasoning with both surfaces and surface networks. SNODP would also benefit greatly if OWL patterns formalizing topological networks and mereo-topological semantics can be incorporated, since the semantics of topological and mereo-topological connections are not explicitly specified in SNODP. Finally, GeoSNODP will benefit from its alignment with a general purpose pattern formalizing the semantics of networks embedded in metric space.

8. Conclusion

The two goals for designing SNODP and GeoSNODP were to clearly understand and formalize surface network theory concepts, and create patterns to serve Linked Topographic Data. If used and adopted by the LTD community, these patterns will unlock a wealth of information in terrain surface datasets, currently outside the realm of Semantic Web technologies. The patterns are also generic enough to support sharing information about surfaces from any other domain. The patterns were created over several months of collaboration between the authors. The pattern design process was largely driven by existing theory, with pragmatic concerns about comprehensibility, simplicity, and reusability also providing useful guidance on how to best implement the patterns in OWL.

The patterns should be relatively comprehensible to most users since the classes directly correspond to topographic features that most people are intuitively familiar with. This paper explains the patterns' design clearly, and should help in pattern comprehension. Since this is the first attempt to formalize surface network theory, and comprehensibility and reusability are paramount, the patterns were designed to be as simple as possible by using the minimum possible number of classes and properties. Specificity of axioms was substantially improved by sidestepping issues exclusively due to rarely occurring cases. Pattern reuse should also be served well by having access to a purely topological pattern, and the flexibility to extend it with a spatial ontology of choice for domain applications. GeoSNODP was created as an example for surfaces from the geospatial domain, but even its alignment with GeoSPARQL is optional—if a better or simpler spatial ontology emerges, SNODP can be alternatively aligned with that ontology.

Surface network patterns are also supposed to serve as data reduction patterns, since they are relatively sparse representations of surface structure. In the case study presented in Section 6, a terrain surface of 1.47 million cells, covering 147 square km, and occupying 13MB storage space (ASCII uncompressed format) was abstracted by less than 500 surface network objects occupying only 3.5 MB (RDF triple format) of storage space. The number of surface network objects increases at a much lower rate with the increase in the number of surface cells. This has great significance for a wide range of applications needing to process high resolution surfaces with billions of points (e.g., LIDAR elevation datasets). Note that SNODP is not compliant with any of the three primary OWL 2 profiles (EL, QL, or RL)[20], so SNODP RDF triple databases are not guaranteed to be tractable for reasoners. However, the need for maintaining pattern expressivity outweighed concerns about any risk of computational intractability since these are small ontologies and surface network datasets are relatively compact.

Regardless of design and efficiency related issues, the adoption of these patterns will really depend on user communities becoming aware of them. The authors are currently focused on how to make these patterns known to researchers and professionals who can benefit from LTD in general, since that provides the best platform for promoting these patterns. Aside from increased visibility from this and related publications in strategic venues, completed and planned follow up GeoVoCamps, conference presentations, and involvement of researchers from the United States Geological Survey are some continuing efforts to increase the community of users. The authors themselves will be using these patterns for a diverse

[19] http://vocamp.org/wiki/GeoVoCampSB2013

[20] http://www.w3.org/TR/owl2-profiles

set of research topics related to landform cognition and topographic information retrieval. A major benefit should come as the authors promote awareness about Linked Topographic Data as an important topic in CyberGIS and Big (Geospatial) Data. The adoption will also be helped by the planned release of a robust version of the software developed for this study for extracting surface networks and converting them to an RDF ontology for the Semantic Web.

While surface network patterns might be adequate for describing some types of terrain objects, as shown by the case study discussions, *several* other topographic and landscape LTD ontologies will still be needed for representing both geoscientific and culturally based concepts relating to topographic eminences, hydrological features, maritime features, vegetation, soil, lithology, settlements, and other source domains of Linked Topographic Data. There exist data related to such domains already, but there is no standardized way to extract objects or describe the semantics of those objects. This research is only a first step, but will hopefully encourage others to design ontology patterns to both support topographic feature extraction and their semantic annotation description—and thereby, helping Linked Topographic Data become less vision and more reality.

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